# Geoacoustic Inversion for Spatially and Temporally Varying Shallow Water Environments

# ONR Special Research Awards in Underwater Acoustics: Entry Level Faculty Award

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## LONG-TERM GOALS

The long-term objective of this work is to develop methods for rapid assessment of seabed variability combined with detailed localized geoacoustic inversions to characterize the bottom for shallow-water environments. Consideration is given to spatial and temporal variability of water column properties common to shallow-water environments and their impact on inversion results. Methods will be developed in recognition of Navy needs for Rapid Environmental Assessment (REA) in littoral regions and corresponding interests in Intelligence, Surveillance, and Reconnaissance (ISR), Anti-Submarine Warfare (ASW), and Mine Warfare (MIW).

## OBJECTIVES

The goals of this project are to develop improved methods for extracting physical seabed parameters in shallow water. Methods will be developed using modal content and dispersion of acoustic fields to determine range dependence in the sediment structure and to construct background models for either linear (perturbative) or non-linear geoacoustic inversion methods such as those based on genetic algorithms (GA) or simulated annealing (SA).

## APPROACH

The approach is based on the analysis of both simulated and measured data representing a variety of geoacoustic environments. Emphasis is placed on parameter extraction for environments with spatially varying sediment properties using both broadband and cw data. Data were collected as part of the ONR sponsored Shallow Water Experiment 2006 (SW06). To infer range-dependent bottom properties in shallow-water waveguides, a set of acoustic experiments were designed and implemented during SW06. The primary receive system was a 48 channel VLA/HLA Shark array deployed and operated by WHOI [1]. Experimental geometries were planned with the 16 channel VLA at the origin. The VLA was moored in 79 m of water with elements spanning 13.5 m to 77.75 m. A J-15-3 low frequency sound source was used for all experiments. The source was towed along radials toward and away from the VLA to create synthetic apertures while broadcasting tones at 50, 75, 125, and 175 Hz. Tow speed was varied with each leg in order to induce a Doppler frequency shift in the Data. Frequencies observed at the receiver for the various tow velocities are shown in Fig. 1. The Doppler shifted data

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14. ABSTRACT
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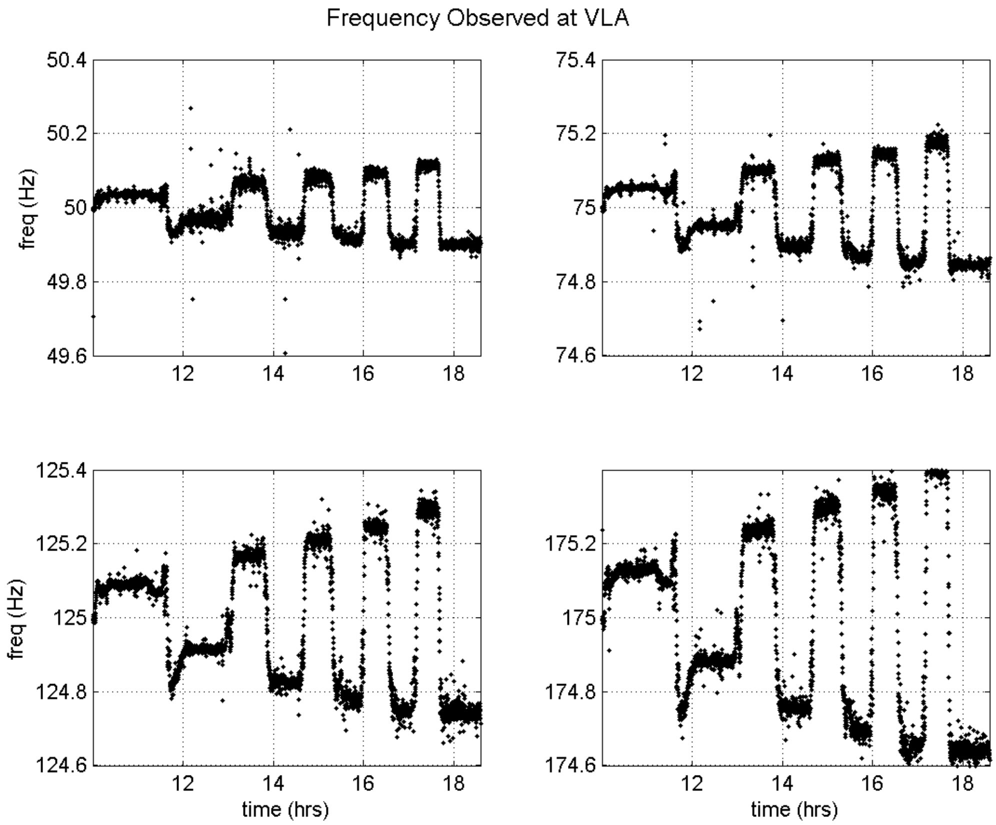


***Fig. 1. Transmit frequencies observed on receivers for source towed toward and away from VLA. Doppler shifts from nominal transmit frequencies of 50, 75, 125 and 175 Hz are consistent with tow speeds that increased in steps from 1 to 5 m/s on alternate tracks.***

were collected in order to validate an approach for estimating modal group velocities using a single source and receiver [2]. In addition to the cw measurements, broadband measurements were made for the J-15 transmitting 0.5 second 40-290 Hz linear sweeps. Sweeps were repeated every 3 seconds with the source located 15 km from the VLA in order to measure modal dispersion characteristics for different aspects. Along with the acoustic data, detailed water column information was acquired using a towed CTD chain. The towed CTD provides a spatial/temporal measure of the temperature and salinity field over the track. The towed CTD chain was deployed concurrently with the source during this work.

The data collected are intended for estimating the modal content of the propagating acoustic field for use as input data to inversion algorithms that yield geoacoustic parameter estimates. From the general experimental setup described, individual experiments were conducted to investigate inversion methods capable of accounting for range-dependence in the seabed that can be measured directly, such as bathymetry, or is unknown, such as that due to sub-bottom sediment intrusions or layer pinching. Specific research areas to be addressed include the continued investigation of high-resolution wave number estimation [3] and modal amplitude [4] techniques, understanding the impact of water column variability on wave number estimation [5][6], and exploring new methods for removing the effects of bathymetry on the measured acoustic fields[7]. In addition, inversion methods are being explored based on modal dispersion for both broadband sources and Doppler shifted cw tones [2][5][8][9].

## WORK COMPLETED

The experimental work described for SW06 was completed in August 2006. During the experiment, this project was allocated 36 hours (12 hours each day 4-6 August, 2006) for acoustic transmissions. At the conclusion of the experiment, 34 hours of data were collected. Over 24 hours of towed cw data were collected along 3 different radials. Tow speeds ranged between 2 and 10 knots. The remaining data were LFMs. LFM data were collected for over 25 different stations on a circle 15 km from the VLA. The acoustic data was retrieved from the VLA/HLA, backed up, and archived for distribution by WHOI. The data were received by the author in December 2006. Algorithms for reducing the raw data to a useable form have been completed. Specific coding has been implemented for demodulating the full time series data into the respective single frequency bands and merging with the spatial track data. The synthetic aperture data are thus reduced to complex pressure as a function of range from the VLA at each of the transmitted frequencies. Code has also been written to produce spatial representations of the sound velocity field in the water column over each of the acoustic track segments.

## RESULTS

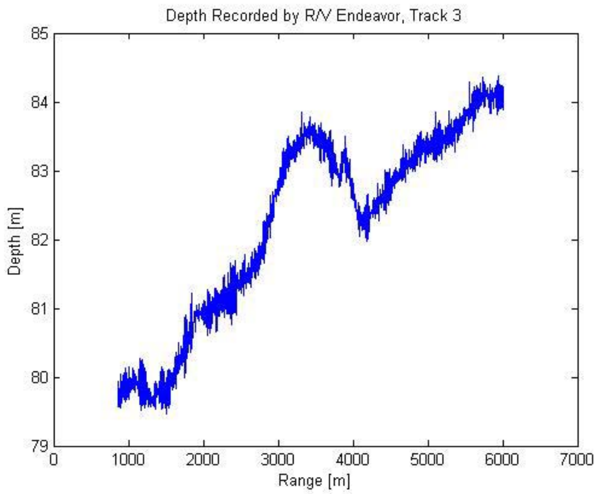


***Fig. 2 In situ bathymetry measured over track of R/V Endeavor during 6 km source tow. Depth generally increases with range away from the VLA and ranges between 80 m and 84 m, with a 2 meter deep trough 3.5 km from the VLA.***

Figure 2 shows the bottom depth measured over a 6 km track that starts 1 km from and extends due East from the VLA. The J-15-3 source was towed repeatedly along this track at different speeds toward and away from the VLA while transmitting a comb of cw tones. Modal eigenvalues as a function of range for 75 Hz data acquired with a source tow speed of 2 m/s and at a depth of 22 m, are shown in Fig. 2. Estimates from two different algorithms are plotted together in the figure. The solid lines represent estimates obtained using a 1500 km aperture autoregressive spectral estimator with a sliding window. The Dashed lines represent the results of a 750 meter short time Fourier transform applied to data that have been filtered so that only a single mode is preserved. The shorter aperture of the mode filtered result reduces the amount of range-averaging in the range-dependent wave number estimates providing higher spatial resolution of local modal eigenvalues. The results from both estimation techniques showed good agreement as seen in Fig 3. The changes with range observed in the figure reflect the sensitivity of individual wavenumber to the measured bathymetry.

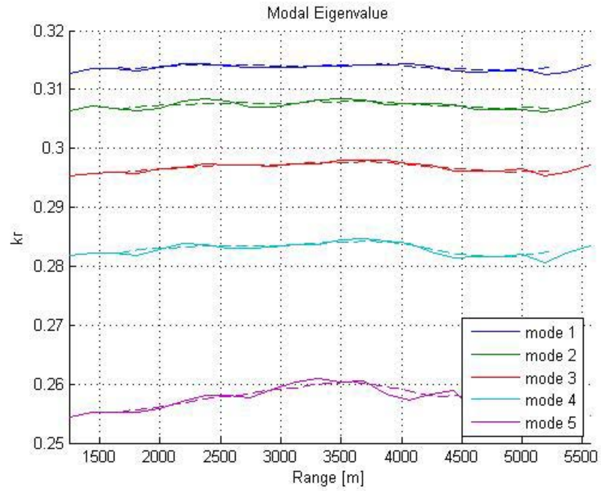


***Fig. 3. Modal eigenvalue estimates as a function of range at 75 Hz. Solid lines are results of 750 m aperture applied to mode filtered pressure field. Dashed lines represent results of 1500 m aperture autoregressive spectral estimator. Range dependence of eigenvalues is consistent with sensitivity to local changes in the measured bathymetry.***

Assuming range-dependence in the modal eigenvalue estimates was primarily caused by local changes in the bathymetry, inversion for sediment sound speed was performed assuming a range-independent environment. A perturbative inversion method [10] was implemented. Using the limited modal eigenvalue data as input, the inversion scheme requires solution of a discrete ill-posed problem. In this work, piecewise polynomial truncated singular value decomposition (PP-TSVD) [11] and qualitative regularization [12] are being investigated for their solution properties. In particular, as in standard regularization the alternative methods act to stabilize the solution of the ill-posed problem. However, in contrast to regularization which is constrained to a smooth solution profile, the alternative approaches allow a discontinuity in the resulting sound speed profile. The solution can thus better approximate the sound speed profile of layered media. The results for an inversion using modal wavenumber estimates at 75 Hz using regularization, PP-TSVD, and qualitative regularization are shown in Fig. 4. The smooth solution resulting from regularization increases from 1650 m/s to 1900 m/s between 0 and 40 m into the sediment. Using PP-TSVD, a layer was found at about 8 meters into the sediment. The sound speed above the layer was approximately 1650 m/s, below the layer, the sound speed was approximately 1780 m/s. Qualitative Regularization is different than PP-TSVD in that it requires *a priori* information about the location of the discontinuity. The solution is then found independently above and below the discontinuity. With the location of the discontinuity provided by PP-TSVD, the sound speed profiles above and below the discontinuity resulting from the different methods were in close agreement.

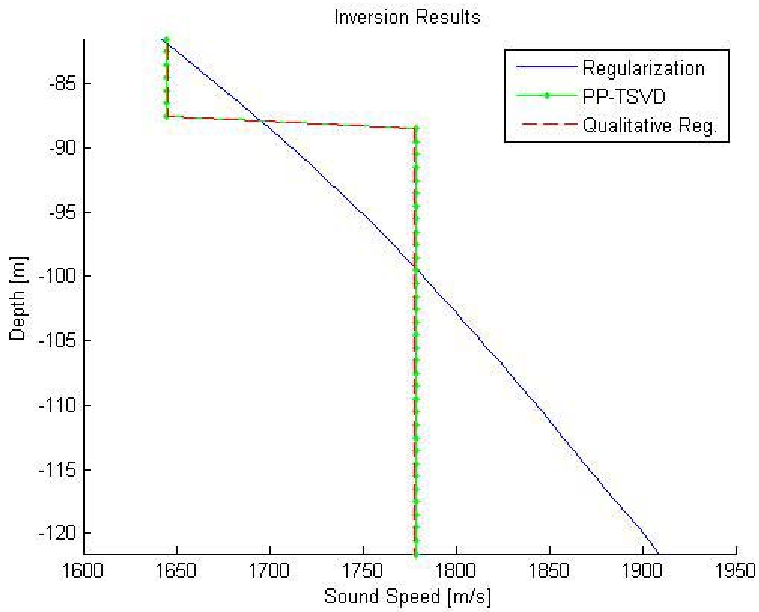


***Fig. 4. Sound speed in the sediment using modal eigenvalues estimates at 75 Hz. Regularization result smoothly increases with depth from 1650 m/s at the water bottom interface to approximated 1900 m/s 40 meters into the bottom. PP-TSVD and Qualitative Regularization resulted in a 8 m layer of 1650 m/s over a 1780 m/s layer down to 40 m.***

Using either PP-TSVD or qualitative regularization, the solutions converged to the final estimates in one or two iterations of the forward model making the algorithms very efficient.

## IMPACT/APPLICATIONS

The application of these results is for geoacoustic inversion in range-dependent shallow water regions. The results are directed to suggest ways to account for and deal with the variability inherent in the watercolumn in shallow regions. In addition, the high-resolution methods reduce the apertures required to extract modal information resulting in more localized inversion results.

## RELATED PROJECTS

This work was a component of SW06. The approaches being developed recognize the complexities of shallow water waveguide environments and seek to account for them. Data and results from these experiments will be shared with and compared with those of other participating PIs. In addition, it is anticipated that the towed CTD chain data will prove invaluable to interpreting results from this experiment and prove itself to be a worth took for consideration in future experimental efforts.

## REFERENCES

[1] A.E.Newhall, T.F. Duda, K. von der Heydt, J.D. Irish, J.N. Kemp, S.A. Lerner, S.P. Libertatore, Y-T Lin, J.F. Lynch, A.R. Maffei, A.K. Morozov, A Shmelev, C.J. Sellers, and W.E. Witzell, Acoustic

and Oceanographic Observations and Configuration Information for the WHOI Moorings from the SW06 Experiment, WHOI Technical Report WHOI-2007-04 (May 2007)
[2] K.M. Becker, Accounting for bias in horizontal wavenumber estimates due to source motion, in *Acoustic Sensing Techniques for the Shallow Water Environment*, eds. A Caiti, N.R. Chapman, J-P Hermand, and S.M. Jesus (Springer Netherlands 2006)
[3] K.M. Becker and G.V. Frisk , Evaluation of an autoregressive spectral estimation technique for determining horizontal wave-number content in shallow water.
*J. Acoust. Soc. Amer.*, **111**, 2288 (2002)
[4] M.S. Ballard and K.M. Becker, A time-frequency distribution based approach for modal eigenvalue estimation in range-dependent shallow-water waveguides, *J. Acoust. Soc. Am.*, 121, pp 3056, (2007)
[5] K.M. Becker and G.V. Frisk, Effects of Sound Speed Fluctuations due to Internal Waves in Shallow Water on Horizontal Wavenumber Estimation. In *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, edited by N.G. Pace and F.B. Jensen (Kluwer, The Netherlands, 2002)
[6] K.M. Becker, Effects of sound speed fluctuations in the water column on geoacoustic parameter estimates. *J. Acoust. Soc. Amer.*, **115**, 2409 (2004)
[7] C. H. Harrison and M. Siderius, Correlations Between Search Parameters in Geoacoustic Inversion, *Proceedings of the Fifth European Conference on Underwater Acoustics, ECUA 2000* Edited by P. Chevret and M.E. Zakharia, Lyon, France (2000)
[8] H. Schmidt and W.A. Kuperman, Spectral and modal representations of the Doppler-shifted field in ocean waveguides, *J. Acoust. Soc. Am.*, **96**(1), (1994)
[9] N. R. Chapman, S. Chin-Bing, D. King, and R. B. Evans, Benchmarking Geoacoustic Inversion Methods for Range-Dependent Waveguides. *IEEE J. Oceanic Eng.*, vol. 28, pp. 320-330 (2003)
[10] S.D. Rajan, J.F. Lynch, and G.V. Frisk, Perturbative inversion methods for obtaining bottom geoacoustic parameters in shallow water, *J. Acoust. Soc. Am.*, **82**(3), pp. 998-1017 (1987)
[11] P.C. Hansen and K. Mosegaard, Piecewise polynomial solutions to linear inverse problems, *Num. Lin. Alg. with Appl.*, **36**(6), pp. 513-524 (1996)
[12] L. Simcik and P Linz, Qualitative regularization: Resolving non-smooth solutions, Technical report CSE-94-12, Dept. of Comp. Science, Univ. of California Davis (1994)

## PUBLICATIONS

K.M. Becker and G.V. Frisk, The impact of water column variability on horizontal wavenumber estimation and mode based geoacoustic inversion results, submitted to *J. Acoust. Soc. Am.*, (August 2007)

K.M Becker, S.D. Rajan, and M.S. Ballard, An overview of the modal inverse methods experiments, Underwater Acoustics Measurements: Technologies and Results, 2nd International Conference, Crete, Greece (June 2007)

M.S. Ballard and K.M. Becker, A time-frequency distribution based approach for modal eigenvalue estimation in range-dependent shallow-water waveguides, *J. Acoust. Soc. Am.*, 121, pp 3056, (2007)